

Charmed-strange Mesons Experimental Results

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Abstract. Two new states in the charm strange sector, $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$, have recently been discovered at e^+e^- collider experiments. The new states are first observed in the dominant $D_s^+\pi^0$ and $D_s^{*+}\pi^0$ modes respectively and are very narrow. They are consistent with 0^+ and 1^+ P-wave $c\bar{s}$ mesons. The $D_{sJ}(2460)^+$ meson is also observed in $D_s^+\gamma$ and $D_s^+\pi^+\pi^-$ modes. A review of the discoveries and possible explanations is given.

INTRODUCTION

In a simplified picture, the charmed-strange meson $c\bar{s}$ (generically denoted as D_{sJ} in this paper) is an atom of a massive charm quark and a light anti-strange quark. The mass splitting of different states is the result of interaction of the spin angular momenta of the two quarks, \vec{s}_c and \vec{s}_s , and the orbital angular momentum \vec{L} between them. According to HQET [1, 2], in the limit that the charm quark is infinitively heavy, its spin is totally decoupled from the light degree of freedom. Then the spin of charm quark \vec{s}_c and $\vec{j} = \vec{L} + \vec{s}_s$ are conserved separately by strong interactions. This is the so-called heavy quark symmetry (HQS).

The charm quark, however, is not infinitively heavy, but it is heavier than the QCD scale Λ_{QCD} . Thus taking $\vec{j} = \vec{L} + \vec{s}_s + \vec{s}_c$ as a good quantum number, the two ground states ($L = 0$, $J^P = 0^-, 1^-$) can be considered as $j = 1/2$ doublets and the four first orbital excited states ($L = 1$) can be treated as $j = 1/2$ doublets ($J^P = 0^+, 1^+$) and $j = 3/2$ doublets ($J^P = 1^+, 2^+$) [2, 3].

Before this year only four of these six states had been observed. All the observed ones are narrow. The 0^- state, D_s^+ , is the lightest D_{sJ} meson and thus can decay only weakly [4]. The 1^- state, D_s^{*+} , was discovered in the electromagnetic radiative mode $D_s^{*+} \rightarrow D_s^+ \gamma$ [5]. The kinematically allowed strong transition $D_s^{*+} \rightarrow D_s^+ \pi^0$ is isospin suppressed, and has branching fraction of only $\sim 6\%$ [6]. The two observed $L = 1$ states are $D_{s1}(2536)^+ \rightarrow D^* K$, and $D_{sJ}(2573)^+ \rightarrow DK$ [7, 8]. Being members of $j = 3/2$ doublets, they decay in D-wave not S-wave, explaining their relatively narrow widths.

The two missing $L = 1$ states (0^+ and 1^+) were predicted by most potential models [9, 10, 11, 12, 13] to be massive enough that they would decay to DK and D^*K , respectively, in a S-wave. The widths were thus expected to be very broad, $\sim 200\text{-}300$ MeV. There were,

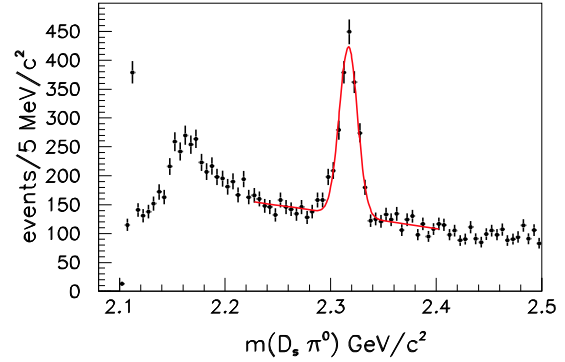


FIGURE 1. The $D_s^+\pi^0$ invariant mass distribution from BaBar.

however, a few predictions that these states would have masses below $D^{(*)}K$ threshold that evidently were not paid much attention [14, 15, 16]. Effectively “everyone” thought that $D^{(*)}K$ were the modes to look for these two states and they were difficult to find due to the large width. The recent discoveries reveal a different picture [17, 18, 19, 20, 21, 22].

DISCOVERY OF $D_{sJ}^*(2317)^+$

The BaBar collaboration observed a $D_s^+\pi^0$ structure in their e^+e^- continuum event sample [17]. The center of peak is $2317.3 \pm 0.4 \pm 0.8$ MeV as shown in Figure 1. The width of the peak is 8.6 ± 0.4 MeV, consistent with their detector resolution. The structure is observed in different D_s^+ decay modes. It does not appear in their generic Monte Carlo simulated sample, and thus it is not a reflection of a previously known decay.

Since the decay products of this new state must contain a charm and an anti-strange quark, it is natural to think

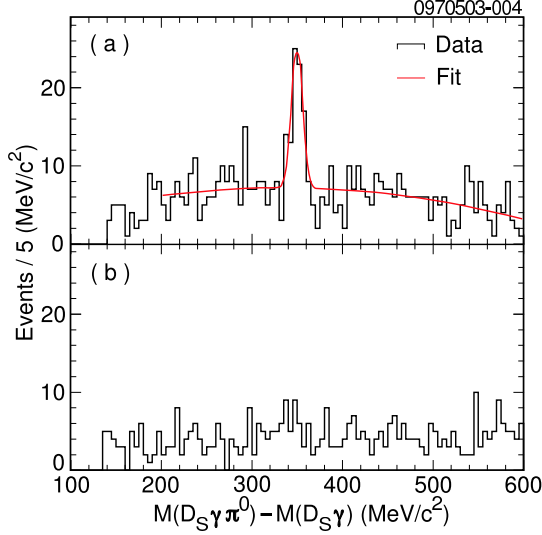


FIGURE 2. The $D_s^+ \gamma \pi^0$ mass distribution from CLEO for $D_s^+ \gamma$ candidates from a) D_s^{*+} signal, b) D_s^{*+} sidebands.

that this is one of the $L = 1$ D_{sJ} mesons that are still missing. Thus it is named as $D_{sJ}^*(2317)^+$. Furthermore, the 1^+ meson is forbidden to decay into $0^- 0^-$, whereas the 0^+ meson is allowed in S-wave. The decay angular distribution is flat after reconstruction efficiency correction, which means either $D_{sJ}^*(2317)^+$ is generated unpolarized or it is a spin-0 state. So this new state is probably the 0^+ D_{sJ} meson, though higher spin is not ruled out.

The mass of $D_{sJ}^*(2317)^+$, however, is much lighter than the 0^+ D_{sJ} meson predicted by most potential models. For example, the model in reference [13] worked quite well with known D and D_{sJ} mesons at the time it was created, and successfully predicted the mass of 0^+ and 1^+ D mesons that were later discovered. It predicted the mass of 0^+ D_{sJ} meson to be 2487 MeV. The newly observed $D_{sJ}^*(2317)^+$ is 170 MeV lower than the expectation, it is even ~ 40 MeV below the DK threshold. And the width is much narrower (< 10 MeV) than the prediction of ~ 200 -300 MeV.

DISCOVERY OF $D_{sJ}(2460)^+$

The CLEO collaboration confirms the $D_s^+ \pi^0$ resonance observed by BaBar [18, 19]. They find that the measured width of the peak is $8.0^{+1.3}_{-1.2}$ MeV, somewhat broader than their detector resolution of 6.0 ± 0.3 MeV. More interestingly they also observe another state, $D_{sJ}(2460)^+$, at 2463 MeV that decays into $D_s^{*+} \pi^0$ (Figure 2).

Figure 2.a shows the invariant mass difference, $\Delta M = M(D_s^+ \gamma \pi^0) - M(D_s^+ \gamma)$. Requiring $D_s^+ \gamma$ consistent with D_s^{*+} , they find 55 ± 10 events in the peak. The center of

peak is measured to be 349.8 ± 1.3 MeV, similar to that of $D_{sJ}^*(2317)^+$ that CLEO finds at 349.4 ± 1.0 MeV in the $\Delta M = M(D_s^+ \pi^0) - M(D_s^+)$ spectrum. The width of peak is 6.1 ± 1.0 MeV, close to the detector resolution of 6.6 ± 0.5 MeV. The BaBar data also shows excess in $D_s^+ \gamma \pi^0$ invariant mass spectrum [17], although the conclusion reached in the publication was that further study is needed due to the complexity of the reflection from the $D_{sJ}^*(2317)^+$.

The ΔM values are very close for $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$. When the D_s^+ from a $D_{sJ}^*(2317)^+$ decay picks up a random photon, the invariant mass of the two can fall in the selection window of D_s^{*+} . Because of the equality of the mass difference, when the π^0 of the same $D_{sJ}^*(2317)^+$ decay is added, the total invariant mass is consistent with $D_{sJ}(2460)^+$. Thus $D_{sJ}^*(2317)^+$ could reflect into $D_{sJ}(2460)^+$ peak, but simulation shows that this peak has width of ~ 15 MeV, much broader than the real $D_{sJ}(2460)^+$ signal peak. Checking the event sample from D_s^{*+} sidebands (Figure 2.b), CLEO find that the reflection of $D_{sJ}^*(2317)^+$ could only account for 1/5 to 1/4 of events in $D_{sJ}(2460)^+$ peak.

The reflection also exists in the opposite direction, when the single photon from $D_{sJ}(2460)^+$ decay is “ignored” and a fake $D_{sJ}^*(2317)^+$ peak is created. With the MC simulation event sample CLEO estimates the cross reflection efficiencies, and then extract the true number of reconstructed $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ signals. In both peaks, about 20% events are due to reflection. The number of $D_{sJ}(2460)^+$ signal is 41 ± 12 , consistent with estimation using D_s^{*+} sidebands.

The Belle collaboration confirms both $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ states in continuum event sample as well as in B decays that will be discussed in next section [20, 21]. They also observed $D_{sJ}(2460)^+$ in $D_s^+ \gamma$ and $D_s^+ \pi^+ \pi^-$ modes. After careful study of cross reflection the BaBar collaboration also confirms the $D_{sJ}(2460)^+$ meson [22]. So there is no doubt about the existence of the $D_{sJ}(2460)^+$ state. As $D_{sJ}(2460)^+$ decays to $1^- 0^-$, it is most probably the missing $J^P = 1^+$ state decays in a S-wave. It can not be a 0^+ state, though other possibilities are not ruled out. Further investigation is needed.

OBSERVATION OF $D_{sJ}^*(2317)^+$ AND $D_{sJ}(2460)^+$ IN B DECAYS

Cross reflection of the two new D_{sJ} states in continuum data complicates the investigation. The cross reflection, however, is eliminated in B decays as extra constraints are applied. Belle searches for $B \rightarrow \bar{D} D_{sJ}^+$ decays of both charged and neutral B [21]. For events whose mass and beam energy constraints are consistent with the $B \rightarrow \bar{D} D_{sJ}^+$ decay, the invariant mass spectrum of

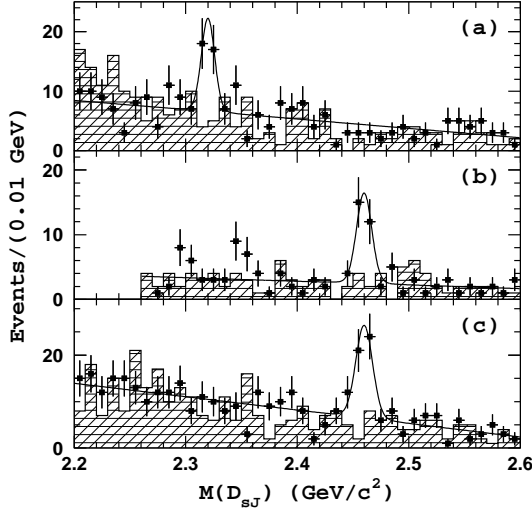


FIGURE 3. Invariant mass for D_{sJ} candidates produced in $B \rightarrow \bar{D} D_{sJ}^+$ decays for $D_{sJ}^+ \rightarrow$ a) $D_s^+ \pi^0$, b) $D_s^{*+} \pi^0$ and c) $D_s^+ \gamma$. The hatched regions are for ΔE sidebands.

$D_s^+ \pi^0$, $D_s^{*+} \pi^0$ and $D_s^+ \gamma$ are shown in Figure 3. Belle observes both the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ in B decays. The peak in Figure 3.c is the first observation of $D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma$ mode. The ratio of partial width of this mode to that of $D_{sJ}(2460)^+ \rightarrow D_s^{*+} \pi^0$ is measured to be $0.38 \pm 0.11 \pm 0.04$, consistent with $0.55 \pm 0.13 \pm 0.08$ measured in continuum data by Belle. The branching fractions are measured to be:

$$\begin{aligned} \mathcal{B}(B \rightarrow \bar{D} D_{sJ}^*(2317)^+) \times \mathcal{B}(D_{sJ}^*(2317)^+ \rightarrow D_s^+ \pi^0) \\ = (8.5_{-1.9}^{+2.6} \pm 2.6) \times 10^{-4}, \\ \mathcal{B}(B \rightarrow \bar{D} D_{sJ}(2460)^+) \times \mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^{*+} \pi^0) \\ = (17.8_{-3.9}^{+4.5} \pm 5.3) \times 10^{-4}, \\ \mathcal{B}(B \rightarrow \bar{D} D_{sJ}(2460)^+) \times \mathcal{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma) \\ = (6.7_{-1.2}^{+1.3} \pm 2.0) \times 10^{-4}. \end{aligned}$$

The B decay provides a much better laboratory to study the spin parity of the new D_{sJ} states. In $B \rightarrow \bar{D} D_{sJ}^+$ decay, the D_{sJ} is totally longitudinally polarized as both B and D are spin-0 particles. Belle measures the helicity angular distribution of $D_{sJ}(2460)^+$ in $D_s^+ \gamma$ mode shown in Figure 4. The measurement strongly supports the 1^+ assignment.

POSSIBLE EXPLANATION AND SEARCH OF OTHER DECAY MODES

The world averaged mass difference are 349.1 ± 0.6 MeV and 346.7 ± 0.8 MeV for $D_{sJ}^*(2317)^+$ and

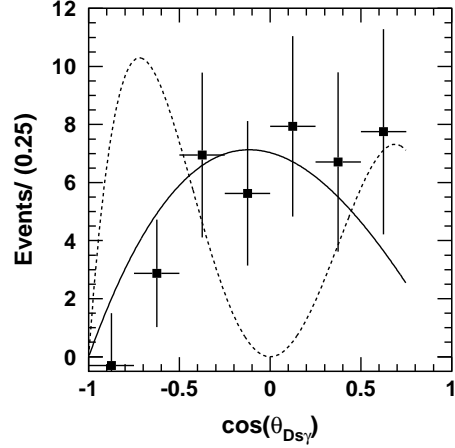


FIGURE 4. Helicity angular distribution of $D_{sJ}(2460)^+$ in $B \rightarrow \bar{D} D_{sJ}(2460)^+$, $D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma$. The solid line is expectation of 1^+ state and dotted line for 2^+ .

$D_{sJ}(2460)^+$ respectively. Adding the PDG value of $M(D_s^+) = 1968.5 \pm 0.6$ MeV and $M(D_s^{*+}) = 2112.4 \pm 0.7$ MeV, the masses are 2317.6 ± 0.8 MeV and 2459.1 ± 1.0 MeV. The upper limits of width at 90% CL are 4.6 and 5.5 MeV respectively set by Belle [21].

Since the discovery of $D_{sJ}^*(2317)^+$ state several possible explanations appeared. Cahn and Jackson use non-relativistic vector and scalar exchange forces and recalculate within potential model to explain the mass [23]. Van Beveran and Rupp use a unitarized meson model to explain the low mass as a threshold effect [24]. Bardeen *et al* explains that it is a normal $c\bar{s}$ state [14, 25]. Barnes *et al* suggest that it is a DK molecule [26]. Several others propose different multi-quark models [27, 28, 29, 30, 31].

Due to the low mass and narrow width, $D_{sJ}^*(2317)^+$ has difficulty fit in the potential models, nor does $D_{sJ}(2460)^+$. They could be DK and D^*K molecules as they are about just 40 MeV below the thresholds. The mass difference between D and D^* is ~ 140 MeV, explaining the mass difference between $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ of ~ 142 MeV. Inside the molecule, $D^{(*)}$ and K are pre-formed. As the direct decay mode $D^{(*)}K$ is closed, quark antiquark pairs of the two have to be broken to form a D_s^+ and a π^0 , thus the decay is weak.

The molecule picture suggests the existence of $D_s^{(*)+} \pi^\pm$ resonances. Observation of these resonances would strongly support molecule hypothesis as they are not conventional $q\bar{q}$ meson due to their quark content. The CDF collaboration studies $D_s^+ \pi^\pm$ modes and find no narrow structure. The CLEO collaboration has searched for $D_s^{(*)+} \pi^\pm$ structures as shown in Figure 5. No narrow structure is found. The productions of narrow $D_s^{(*)+} \pi^\pm$

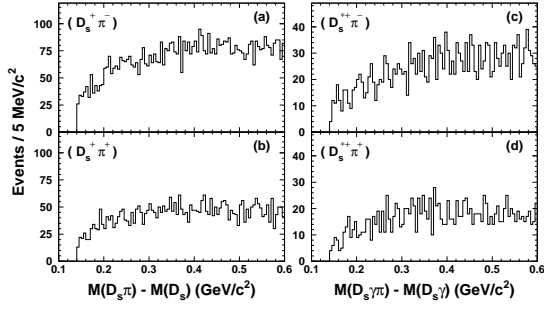


FIGURE 5. $D_s^{(*)+} \pi^\pm$ mass distribution from CLEO for a) opposite-signed $D_s \pi$, b) same-signed $D_s \pi$, c) opposite-signed $D_s^* \pi$ and d) same-signed $D_s^* \pi$.

states are at least a factor of ten lower than the $D_s^{(*)+} \pi^0$ modes. This proves that $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ are iso-scalars. It, however, does not totally rule out the molecule scenario as an iso-vector molecule is expected to be broad, although there is no indication of the existence of such structure in B decay sample.

The new D_{sJ} states fit in well the quark model as normal 0^+ and 1^+ $c\bar{s}$ mesons except for maybe the low masses. Bardeen *et al* couple chiral perturbation theory with a quark model representing HQET, and in fact predicted the masses of the 0^+ and 1^+ $c\bar{s}$ mesons below $D^{(*)}K$ thresholds. The narrow widths are due to isospin violation in the decays. They infer that $D_{sJ}^*(2317)^+$ is indeed the 0^+ $c\bar{s}$ meson. It has an 1^+ partner with mass splitting identical to that between 0^- and 1^- $c\bar{s}$ mesons, which is backed up by the measurements. They also calculate partial width of other decay modes as shown in Table. 1. The measured ratios and limits (at 90% C.L.) from CLEO and Belle are also listed. The predictions are consistent with the measurements, and thus this explanation is favored.

Factorization implies that the branching fractions of $B \rightarrow \bar{D} D_{sJ}^+$ for the new D_{sJ} states be similar to that of D_s^+ and D_s^{*+} , which are $\sim 1\%$. The measurements are about a factor of ten lower. This casts a shadow on the favored conventional $c\bar{s}$ explanation. Four-quark or molecule states, however, would have branching fraction consistent with the measurements [28, 31, 32]. Browder *et al* propose that these states are mixtures of $c\bar{s}$ and four-quark states [33]. More experimental measurements and theoretical ideas are needed to reveal the true identity of these two new states.

TABLE 1. Ratio of branching fractions of different $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ modes. Limits are with 90% CL.

$D_{sJ}^*(2317)^+$ decay	BEH	Belle	CLEO
$D_s^+ \pi^0$	$\equiv 1$	$\equiv 1$	$\equiv 1$
$D_s^+ \pi^+ \pi^-$	0	$< 4 \times 10^{-3}$	< 0.019
$D_s^+ \gamma$	0	< 0.05	< 0.052
$D_s^{*+} \pi^0$	0		< 0.01
$D_s^{*+} \gamma$	0.08	< 0.18	< 0.059
$D_{sJ}(2460)^+$ decay	BEH	Belle	CLEO
$D_s^{*+} \pi^0$	$\equiv 1$	$\equiv 1$	$\equiv 1$
$D_s^{*+} \gamma$	0.22	< 0.31	< 0.16
$D_s^+ \pi^0$	0	< 0.21	
$D_s^+ \pi^+ \pi^-$	0.20	0.14 ± 0.04	< 0.08
$D_s^+ \gamma$	0.24	0.44 ± 0.09	< 0.49
$D_{sJ}^*(2317)^+ \gamma$	0.13		< 0.58

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REFERENCES

- De Rujula, A., Georgi, H., and Glashow, S. L., *Phys. Rev. Lett.*, **37**, 785 (1976).
- Isgur, N., and Wise, M. B., *Phys. Rev. Lett.*, **66**, 1130 (1991).
- Godfrey, S., and Kokoski, R., *Phys. Rev.*, **D43**, 1679 (1991).
- Chen, A., et al., *Phys. Rev. Lett.*, **51**, 634 (1983).
- Albrecht, H., et al., *Phys. Lett.*, **B146**, 111 (1984).
- Gronberg, J., et al., *Phys. Rev. Lett.*, **75**, 3232 (1995).
- Albrecht, H., et al., *Phys. Lett.*, **B230**, 162 (1989).
- Kubota, Y., et al., *Phys. Rev. Lett.*, **72**, 1972 (1994).
- Godfrey, S., and Isgur, N., *Phys. Rev.*, **D32**, 189 (1985).
- Zeng, J., Van Orden, J. W., and Roberts, W., *Phys. Rev.*, **D52**, 5229 (1995).
- Gupta, S. N., and Johnson, J. M., *Phys. Rev.*, **D51**, 168 (1995).
- Ebert, D., Faustov, R. N., and Galkin, V. O. [hep-ph/9809285].
- Di Pierro, M., and Eichten, E., *Phys. Rev.*, **D64**, 114004 (2001).
- Bardeen, W. A., and Hill, C. T., *Phys. Rev.*, **D49**, 409 (1994).
- Fayyazuddin, and Riazuddin, *Phys. Rev.*, **D48**, 2224 (1993).
- Deandrea, A., Gatto, R., Nardulli, G., Polosa, A. D., and Tornqvist, N. A., *Phys. Lett.*, **B502**, 79 (2001).
- Aubert, B., et al., *Phys. Rev. Lett.*, **90**, 242001 (2003).
- Stone, S., and Urheim, J., *AIP Conf. Proc.*, **687**, 96–104 (2003).
- Besson, D., et al., *Phys. Rev.*, **D68**, 032002 (2003).
- Abe, K., et al. [hep-ex/0307052].
- Krokovny, P., et al. [hep-ex/0308019].

- 22. Aubert, B., et al. [hep-ex/0310050].
- 23. Cahn, R. N., and Jackson, J. D., *Phys. Rev.*, **D68**, 037502 (2003).
- 24. van Beveren, E., and Rupp, G., *Phys. Rev. Lett.*, **91**, 012003 (2003).
- 25. Bardeen, W. A., Eichten, E. J., and Hill, C. T., *Phys. Rev.*, **D68**, 054024 (2003).
- 26. Barnes, T., Close, F. E., and Lipkin, H. J., *Phys. Rev.*, **D68**, 054006 (2003).
- 27. Szczepaniak, A. P., *Phys. Lett.*, **B567**, 23 (2003).
- 28. Cheng, H.-Y., and Hou, W.-S., *Phys. Lett.*, **B566**, 193 (2003).
- 29. Terasaki, K., *Phys. Rev.*, **D68**, 011501 (2003).
- 30. Nussinov, S. [hep-ph/0306187].
- 31. Datta, A., and O'Donnell, P. J., *Phys. Lett.*, **B567**, 273 (2003).
- 32. Chen, C.-H., and Li, H.-n. [hep-ph/0307075].
- 33. Browder, T. E., Pakvasa, S., and Petrov, A. A. [hep-ph/0307054].